Coherence of Low-Frequency Sound Signals Propagating through a Fluctuating Ocean: Analysis and Theoretical Interpretation of 2004 NPAL Experimental Data

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LONG-TERM GOALS

To theoretically study low-frequency, long-range sound propagation in a fluctuating ocean, including studies of 3D effects.

To compare obtained theoretical results with NPAL experimental data.

OBJECTIVES

To complete development of a new, modal, 3D theory of low-frequency, long-range sound propagation through an ocean with random inhomogeneities.

Based on this theory, to finalize computer codes for calculating statistical moments of a sound field propagating through the ocean with internal gravity waves.

To continue comparison between theoretical predictions and data obtained during the 1998-1999 and 2004 NPAL experiments.

APPROACH

Coherence of low-frequency sound waves propagating over long ranges in the ocean diminishes considerably due to internal waves (IW) and spice. Therefore, studies of the coherence function and other statistical moments of low-frequency sound waves propagating over long ranges in a fluctuating ocean are important for assessment of performance of large acoustic arrays and related problems. These studies have been done in many works by different approaches, e.g. see [1,2,3,4]. For low-frequency, long range sound propagation through a fluctuating ocean, a modal approach seems to be a most adequate [5]. Using this approach, closed equations for the coherence function in a 3D fluctuating ocean were derived in a number of papers (see [6] and references therein). However, most of these equations are too involved to be solved numerically even with the use of modern computers.

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The main goal of this project is to complete development of a new, modal, 3D theory of low-frequency, long-range sound propagation in a fluctuating ocean which allows to calculate numerically the coherence function and to study its dependence on different parameters of the problem, e.g. frequency, range, hydrophone depth, etc. Other goals of the project are development of computer codes (based on the modal, 3D theory) for calculation of the coherence function; development of computer codes for processing of low-frequency sound signals recorded during the 1998-1999 and 2004 North Pacific Acoustic Laboratory (NPAL) experiments [7,8]; and comparison between theoretical results and experimental data.

WORK COMPLETED

During the reporting period, the following tasks were accomplished:

Task 1. A new, modal, 3 D theory of sound propagation in a fluctuating ocean was developed further by assuming that a random ocean is statistically isotropic in a horizontal plane and a sound source is omni-directional. The results obtained were summarized in Ref. [10,12].

Task 2. Based on this modal, 3D theory, computer codes were developed to calculate the coherence function and some other statistical characteristics of a sound field propagating in a random ocean with IW. The corresponding results are presented in Ref. [12].

RESULTS

The following results were obtained in FY07:

Task 1.
In our previous ONR project [9], first results in development of a new, modal, 3D theory of low-frequency, long range sound propagation through a fluctuating ocean were obtained and summarized in Ref. [6]. The theory is based on partition of the sound propagation path into many slabs, within each of which the Chernov method is used to calculate the first and second statistical moments of a sound field. Then, these statistical moments are recalculated from one slab to another, yielding the mean sound field and the coherence function at the receiver location. The derived equations for the coherence function allowed us to obtain some numerical results for the considered problem. However, these equations are still too complicated for detailed numerical analysis of dependence of the coherence function on parameters of the problem.

During the reporting period, the modal, 3D theory was developed further. In this development which was summarized in Refs. [10,11,12], we took into account that random inhomogeneities in the ocean can be usually assumed as statistically homogeneous in a horizontal plane and a sound source is omni-directional. In this case, it is worthwhile to use a cylindrical coordinate system and to decompose the sound field into a sum of athimuthal harmonics. Then, the sound propagation path is partitioned into many slabs (which are cylindrical now) and the Chernov method is used to obtain a closed equation for the second moment within each slab.

As a result, the developed theory gives an explicit expression for the coherence function of a sound field propagating in a random ocean. A dimension of a scattering matrix appearing in the solution is much smaller than those in previous works. This makes the developed theory readily amenable for

numerical studies of dependence of the coherence function on parameters of the problem. It should also be noted that the obtained solution for the coherence function conserves acoustic energy.

Task 2.
Based on the modal, 3D theory, computer codes were developed to calculate the coherence function and other statistical characteristics of a sound field propagating in an oceanic waveguide with an IW field. Some of the results obtained are presented below.

Figure 1 shows the absolute values of the cross-modal correlation functions I_{nm} versus the acoustic mode numbers n and m for four sound propagation ranges R. For these calculations, the sound frequency $f = 75$ Hz and the source depth $z_s = 807$ m. It follows from the figure that cross-modal correlation dramatically decreases with range R so that for $R = 1000$ km acoustic modes with different mode numbers practically do not correlate. Furthermore, equapartization of the mode intensities I_{nn} with increase in range is seen in Fig.1.

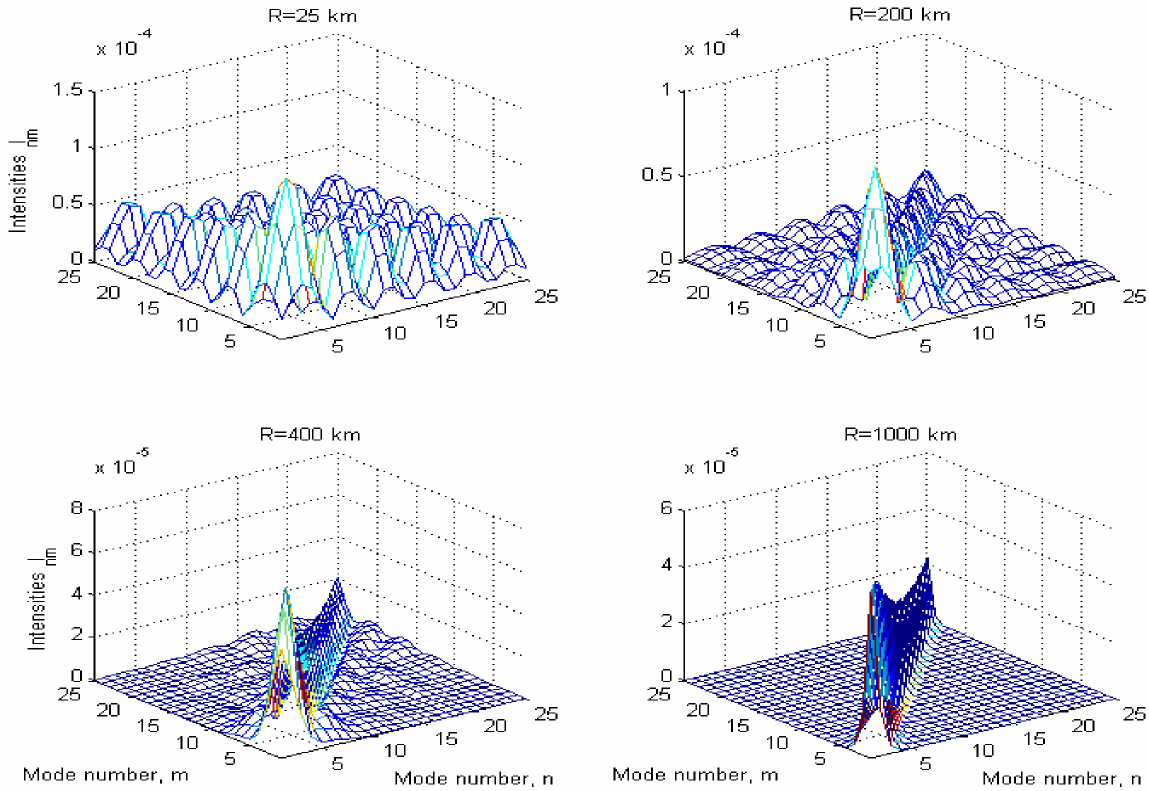

Figure 1. Magnitudes of cross-modal correlation functions I_{nm}
versus mode numbers n and m for different sound propagation ranges R.

This effect can be seen more clearly in Fig. 2 where the mode intensities I_{nn} are plotted versus the mode number n for different ranges R. For $R = 25$ km, I_{nn} looks like a random function of n. However for $R = 1000$ km, the values of I_{nn} are close to each other. The numerical results obtained but not presented here also showed that for relatively large ranges (about 4000 km) the values of the mode intensities I_{nn} are almost the same.

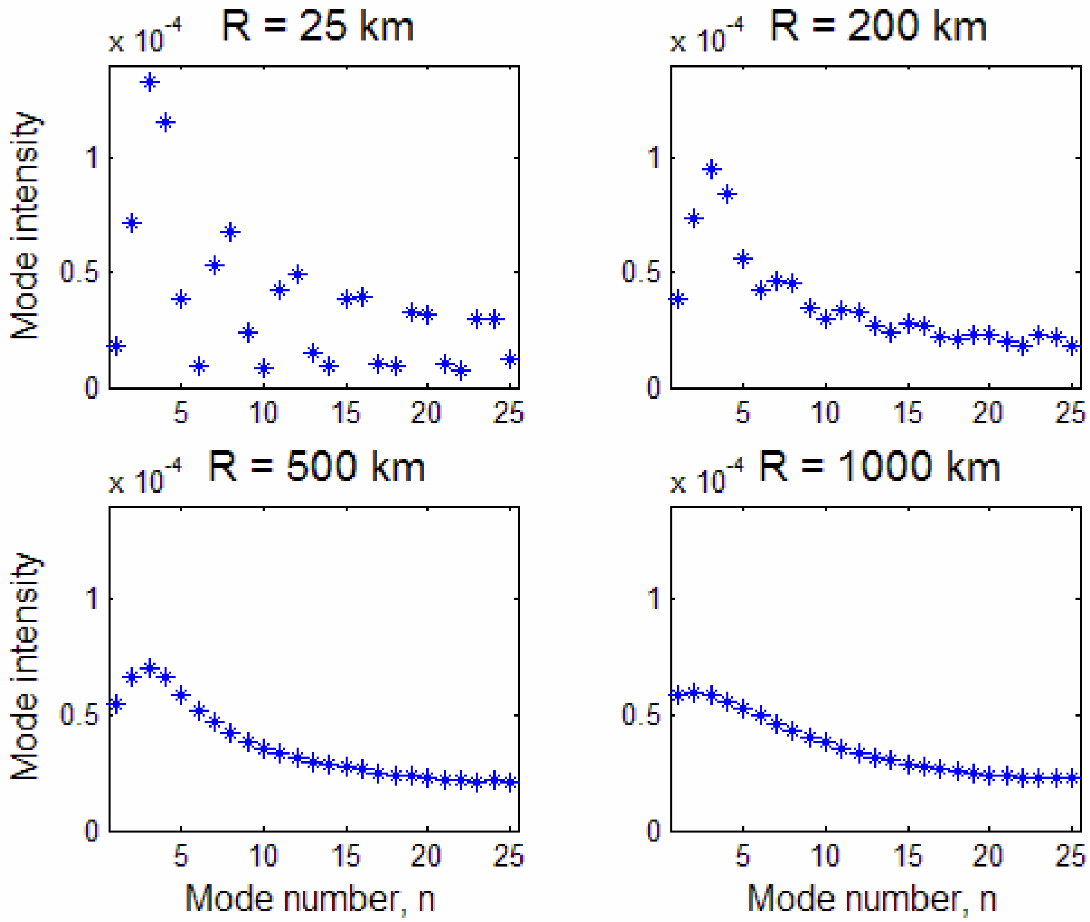

Figure 2. Mode intensities I_{nn} versus the mode number n for different propagation ranges R.

The dependence of the mean sound intensity (normalized by its maximal value) on the receiver depth is depicted in Fig. 3 for four ranges R. In calculations, the sound frequency $f = 75$ Hz (as in previous two figures), however the source depth is different: $z_s = 350$ m. For $R = 25$ km, a sharp maximum in the mean sound intensity is seen at the source depth. As R increases, scattering tends to redistribute acoustic energy over the ocean depth. Furthermore, a second maximum in the mean sound intensity is formed at the depth conjugated to the source depth.

Vertical coherence of the sound field is shown in Fig. 4, with left and right plots being experimental results and theoretical predictions, respectively. Shown is the magnitude of the correlation coefficient K of the sound fields at two hydrophones versus their depths. The experimental data were recorded during the 2004 NPAL experiment and processed using a code developed. Acoustic signals were

recorded on 266 day 20 h 06 min 40 sec of the experiment by the upper part of the shallow VLA in the depth range from 400 m to 1100 m. The distance between the source and VLA was $r = R = 1000$ km, the source depth $z_s = 350$ m, the carrier of the sound frequency $f = 68.2$ Hz, and the acoustic signal emitted by the source was truncated to the first 300 s. In the left plot, the main "ridge" (where $K = 1$) corresponds to the correlation of the acoustic signal recorded by a hydrophone with itself. In addition to the main ridge, two-three smaller ridges can be seen in the left plot where K is less than 1. The rest of the correlation coefficient looks like a noise. A right plot in Fig. 4 depicts the correlation coefficient K calculated numerically with the use of the

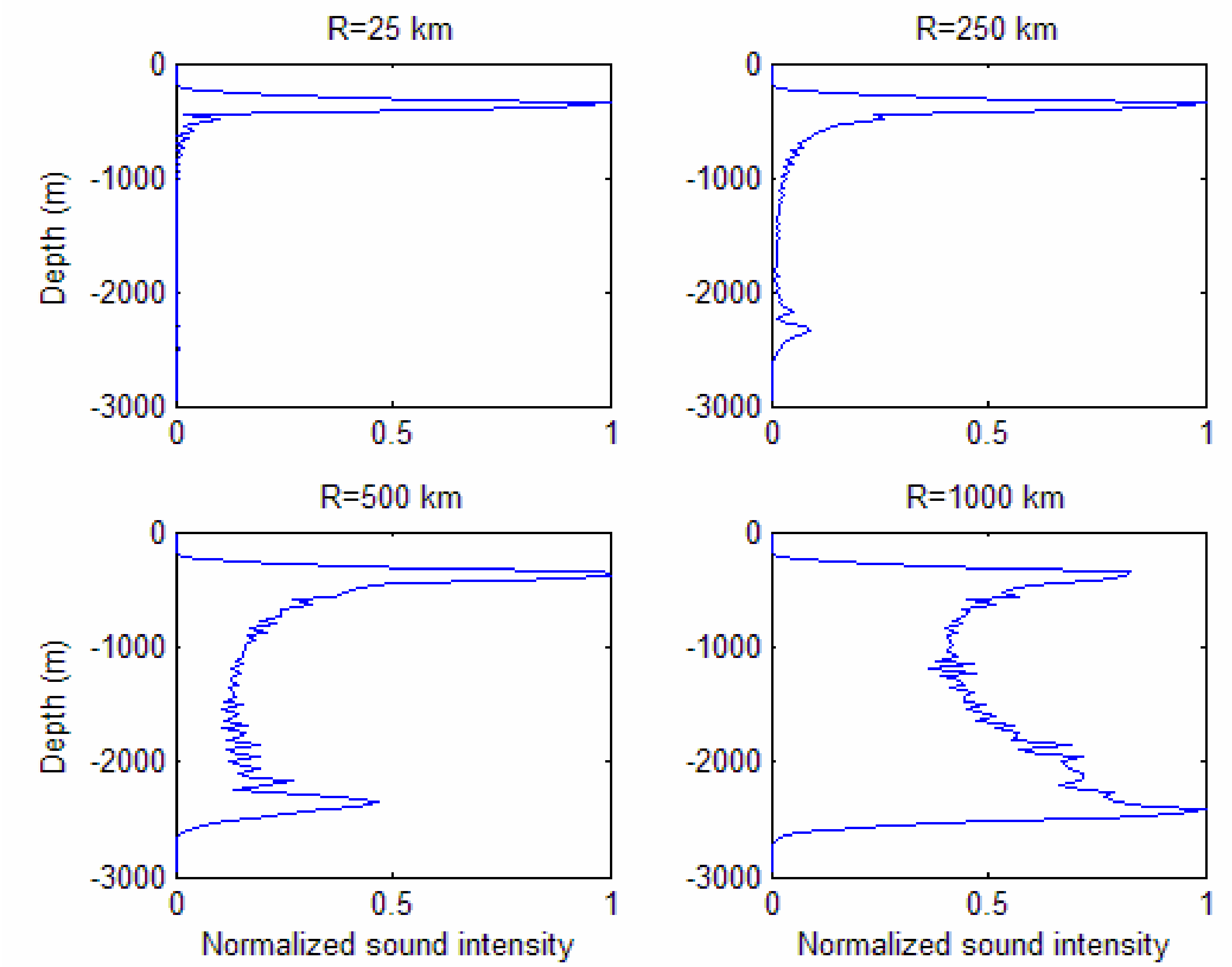

Figure 3. Mean intensity of the sound field versus depth for different propagation ranges R.

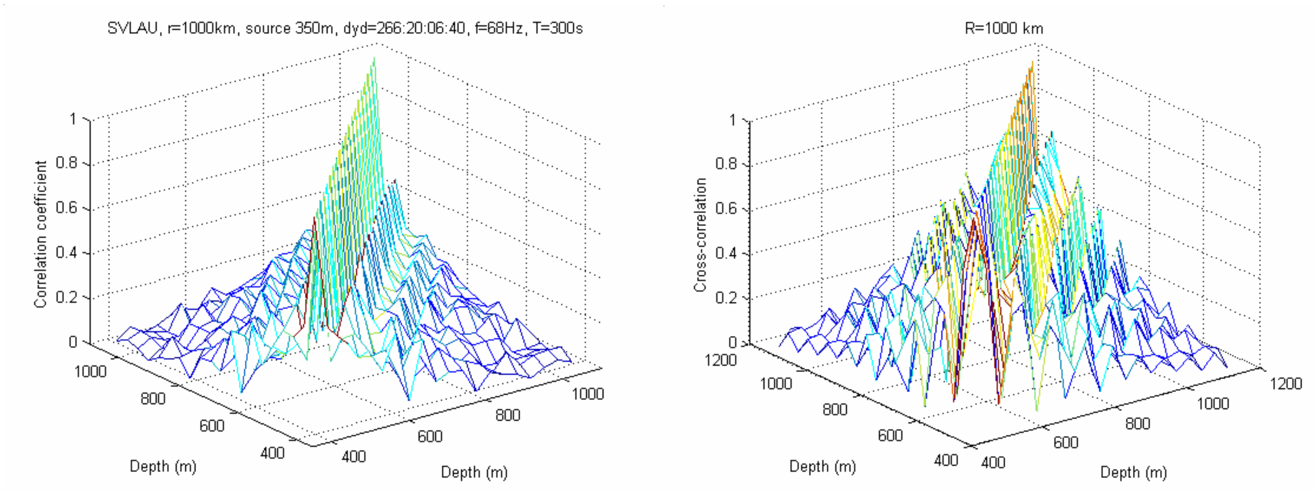

Figure 4. The magnitude of the correlation coefficient K at two hydrophones versus their depths. Left plot correspond to the 2004 NPAL experiment, right plot is theoretical predictions.

modal, 3D theory. Small ridges can also be seen in the right plot so that experimental results and theoretical predictions qualitatively agree. Quantitative comparison between the experiment and theory requires additional work (accounting for the real sound speed profile, bathymetry, final band width, etc.) and will be done in the future.

Finally, Fig. 5 shows the normalized coherence function (calculated with the use of the modal, 3D theory) versus the horizontal separation of hydrophones. For these calculations, $f = 75$ Hz, $z_s = 807$ m, and $R = 1000$ km. It follows from the figure that the coherence radius is about 1500 m that qualitatively agrees with those measured during the NPAL experiments, e.g. see [6].

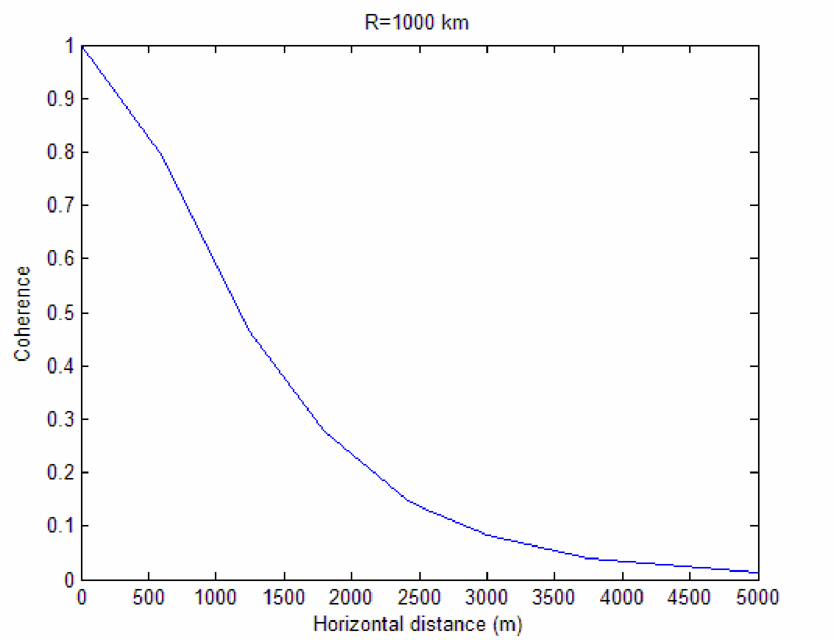

Figure 5. The normalized coherence function versus the horizontal separation between hydrophones.

IMPACT/APPLICATIONS

Using the modal, 3D theory of sound propagation in a fluctuating ocean and assuming that random inhomogeneities are statistically homogeneous in a horizontal plane, an explicit expression for the coherence function due to a monochromatic, omni-directional source was obtained. Computer codes were developed to calculate numerically the coherence function and other statistical characteristics of the sound field.

RELATED PROEJCTS

1. The 1998-1999 NPAL experiment, see Ref. [7].
2. The 2004-2005 NPAL experiment, see Ref. [8].
3. “Multiple Scattering of Sound by Internal Waves and Acoustic Characterization of Internal Wave Fields in Deep and Shallow Water”, ONR projects N00014-05-IP2-0024 and N00014-06-1-0010.

REFERENCES

1. S. M. Flatte, R. Dashen, W. H. Munk, K. M. Watson, and F. Zachariasen, *Sound Transmission Through a Fluctuating Ocean* (Cambridge University Press, 1979).

2. E. Yu. Gorodetskya, A. I. Malekhanov, A. G. Sazontov, N. K Vdovicheva, “Deep-water acoustic coherence at long ranges: Theoretical prediction and effects on large array signal processing,” IEEE J. Oceanic Eng. **24**, No2, 156-170 (1999).

3. C. Penland, “Acoustic normal mode propagation through a three-dimensional internal wave field,” J. Acoust. Soc. Am. **78**, 1356 - 1365 (1985).

4. A. G. Voronovich and V. E. Ostashev, “Mean field of a low-frequency sound wave propagating in a fluctuating ocean,” J. Acoust. Soc. Am. **119** (4), 2101-2105 (2006).

5. L. B. Dozier and F. D. Tappert, “Statistics of normal mode amplitudes in a random ocean. I. Theory,” J. Acoust. Soc. Am. **63**, 353-365 (1978).

6. A. G. Voronovich and V. E. Ostashev, “Low-frequency sound scattering by internal waves,” J. Acoust. Soc. Am. **119** (3), 1406-1419 (2006).

7. P. F. Worcester and R. C. Spindal, "North Pacific Acoustic Laboratory", J. Acoust. Soc. Am. **117**, No 3, Pt. 2, 1499-1510 (2005).

8. P. F. Worcester: http://dropbox.ucsd.edu/~pworcester/NPAL04_Documents.

9. A. G. Voronovich and V. E. Ostashev, "Low-frequency, long-range sound propagation through a fluctuating ocean: Analysis and theoretical interpretation of existing and future NPAL experimental data," ONR Project No N0001404IP20009 (2003-2006).

PUBLICATIONS

10. A. G. Voronovich and V. E. Ostashev, "Coherence function of a low-frequency sound field in an oceanic waveguide with random inhomogeneities," 19th International Congress on Acoustics, Madrid, Spain, 2-7 September (2007) [published].

11. A. G. Voronovich and V. E. Ostashev, "Vertical coherence of low-frequency sound waves propagating through a fluctuating ocean," J. Acoust. Soc. Am. **120** (5) Pt. 2, 3061-3062 (2006) [published].

12. A. G. Voronovich and V. E. Ostashev, "Coherence function of a sound field in an oceanic waveguide with horizontally isotropic random inhomogeneities", J. Acoust. Soc. Am. (2007) [in press].